Chapter 6

# The Cassini Era: 1996–1997

## THE CASSINI ERA

### Winds of Change

Throughout its life, the form of the DSN at any single point in time was shaped by many forces acting on it simultaneously and often in different directions. These forces included budget constraints from the NASA Office of Tracking and Data Acquisition (Code O), the requirements for support of new missions from the NASA Office of Space Science (Code S), the drive of new technology, the pressure of real-time operations, and the concerns of foreign agencies and competing requirements for limited antenna time from radio astronomy and other space science constituencies. Dealing with these often conflicting currents had become a way of life at all levels within the DSN structure, and the remarkable progress recorded in the forthcoming pages attests to the high degree of success that was achieved.

By 1995, however, the winds of change were blowing more strongly than ever before throughout NASA, and by 1997 their effect was being keenly felt in the DSN. The changes would affect the established purpose, scope, and functions of the DSN, and

**Cassini Era Mission Set**

| Deep Space Missions (Launch) | Earth-Orbiter Missions |
|---|---|
| *Galileo* (1989) | ISTP-Soho |
| Voyager (1977) | ISTP-Polar |
| *Ulysses* (1990) | ISTP-Wind |
| *Pioneer 10* (1972) | ISTP-Geotail |
| N-E Asteroid Rndv. (2/17/96) | IR Space Observatory |
| *Mars Global Surveyor* (11/7/97 | ASTRO-D |
| *Mars Pathfinder* (12/04/96) | TOMS-EP |
| *Cassini* (10/15/97) | YOHKOH Solar-D |
| | Space Tech. Res. Vehicle A |
| | Radar Satellite |
| | Roentgen Satellite |
| | SURF Satellite-1 |
| | SSTI-Lewis |
| | Hotbird-2,-3 |
| | HALCA |

Figure 6-1. Cassini Era mission set, 1997.

they first appeared in the Telecommunications and Mission Operations Directorate (TMOD) Implementation Plan for Fiscal Year 1998.[1] This plan is discussed fully in a later chapter.

This chapter will review the DSN and the missions it was supporting as the Galileo Era came to an end and the Cassini Era opened to an environment of change.

## The Cassini Era Mission Set

A snapshot of the DSN operational tracking schedule in 1997 would have revealed the portfolio of deep space and Earth-orbit missions shown in Figure 6-1. This represented the DSN mission set for the first year or two of the Cassini Era.

Except for Ulysses, which was an ESA mission, all of the deep space missions were of NASA origin. Half of the missions, Galileo, Voyager, Ulysses, and *Pioneer 10*, were older missions that had been in the DSN for many years and have been discussed in previous chapters. The Near-Earth Asteroid Rendezvous, Mars Global Surveyor, Mars Pathfinder, and Cassini missions were new in 1996 and 1997, and brought with them new challenges and changes for the DSN.

## DEEP SPACE MISSIONS

### General

Through the end of the Galileo Era and the beginning of the Cassini Era, the ongoing deep space missions, Galileo, Ulysses, *Pioneer 10*, and *Voyagers 1* and *2*, presented no new challenges for the DSN. They continued to return science and engineering data, each according to its own remaining capability, and were provided with minimal tracking station support, sufficient only to maintain their viability as scientific missions. The changes and upgrades that had been incorporated into the DSN since these missions began had always maintained a capability to handle their diminishing requirements for telecommunications and data acquisition support.

### Galileo

Amongst the aging missions, Galileo was the most active. As described in the previous chapter, *Galileo* had completed its primary mission in December 1997 and continued at a much reduced pace to carry out further observations of Europa under the name Galileo Europa Mission. It remained entirely dependent upon arraying of the DSN 70-m/34-m antenna for its downlinks, since the Parkes antenna was no longer available to support the arrayed configurations.

### Ulysses

As the *Ulysses* spacecraft embarked on its second 6.2-year orbit over the poles of the Sun, its science instruments continued to perform normally. The north and south polar passes were planned for 2000 and 2001, respectively. On this orbit, the properties of solar winds in high solar latitudes during the maximum of the solar activity cycle were to be investigated. Through 1997, Earth-pointing maneuvers and instrument calibrations were made regularly, in preparation for observations during the fifth solar opposition in March 1998. Daily passes on the 34-m antennas at S-band or X-band, and telemetry running at 512 bits per second to 2,048 bits per second, were typical of this period.

### Voyagers 1 and 2

The continuation of the *Voyager 1* and *2* missions beyond the outer planets was called the Voyager Interstellar Mission (VIM) and would continue through the year 2019. Through 1996 and 1997, *Voyager 1* and *Voyager 2* maintained a presence on the DSN tracking schedules with several passes per week for each spacecraft on the 34-m antennas, with occasional support on the 70-m antennas.

At approximately 2:10 p.m. Pacific time on 17 February 1998, according to VIM project manager Ed B. Massey, *Voyager 1* reached an Earth-to-spacecraft range of 10.4 billion km (6.5 billion miles), exceeding the record held by Pioneer 10 for 25 years, and became the most distant human-made object in space. Almost 70 times farther from the Sun than Earth (70 AU), with the radio signal taking 9 hours and 36 minutes to travel from the spacecraft to Earth, *Voyager 1* was then at the very edge of the solar system. The downlink data rate was 160 bits per second or 600 bits per second on the 34-m antennas and could be increased to 1.4 kilobits per second on the 70-m antennas when required for tape recorder playback. At a smaller distance of 52 AU, *Voyager 2* was being supported by the southern hemisphere stations in Canberra and could receive downlink data at 7.2 kilobits per second.

JPL marked the event with a special press release,[2] "*Voyager 1* Now Most Distant Human-Made Object In Space." The article explained the scientific significance of this remarkable achievement:

> Having completed their primary explorations, *Voyager 1* and its twin *Voyager 2* were studying the environment of space in the outer solar system. Although they were beyond the orbit of all the planets, the spacecraft remained well within the boundary of the Sun's magnetic field, called the heliosphere. Science instruments on both spacecraft sensed signals that scientists believed were coming from the outermost edge of the heliosphere, known as the heliopause. The heliosphere results from the Sun's emission of a steady flow of electrically charged particles called the solar wind. As the solar wind expands supersonically into space in all directions, it creates a magnetized bubble—the heliosphere—around the Sun. Eventually, the solar wind encounters the electrically charged particles and magnetic field in the interstellar gas. In this zone, the solar wind abruptly slows down from supersonic to subsonic speed, creating a termination shock. Before the spacecraft travel beyond the heliopause into interstellar space, they will pass through this termination shock. Dr. Edward C. Stone, Voyager project scientist and director of JPL, said, "The data coming back from *Voyager* now suggest that we may pass through the termination shock in the next three to five years. If that's the case, then one would expect that within ten years or so, we would actually be very close to penetrating the heliopause itself and entering into interstellar space for the first time."

> Reaching the termination shock and heliopause would be major milestones for the mission because no spacecraft had been there before, and the *Voyagers* would gather the first direct evidence of their structure. Encountering the termination shock and heliopause had been a long-sought goal for many space scientists. Exactly where these two boundaries were located and what they were like remained a mystery.

Although these were significant long-range telecommunications records for the DSN, uplink and downlink communications with both spacecraft remained routine matters. With plenty of performance margin still remaining, the DSN expected to be able to support the VIM for the next twenty years.

### *Pioneer 10*

After an active life of 25 years, the *Pioneer 10* mission came to an end on 31 March 1997, with the last track at DSS 63. Launched on 2 March 1972 and tracked by the DSN ever since, *Pioneer 10* support had almost become a permanent feature of routine DSN activity. Although the downlink was still running at 8 bps, the signal was very weak, and it had been determined that the science value of the data being returned was no longer sufficient to justify further continuation of the mission. Pioneer operations had been conducted from the mission control center at the Ames Research Center in Sunnyvale, California, for many years, and the mission had many notable scientific achievements to its credit. By 1983, it had become the first spacecraft to travel beyond the orbits of Neptune and Pluto. Following a solar system escape trajectory away from the Sun, it continued to move further outward in search of the heliopause, the region of the solar system where the influence of the Sun itself finally ends and true interstellar space begins. Now, following a trajectory in the opposite direction to that of *Pioneer 10*, the pursuit of that goal would be taken over by Voyager. In the immediate future, the *Pioneer 10* spacecraft would be used by the DSN operations group at JPL to train new station controllers for future missions.

## Near-Earth Asteroid Rendezvous

The Near-Earth Asteroid Rendezvous (NEAR) mission was the first in NASA's Discovery program of lower cost, highly focused planetary science missions. It was developed and managed by the Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland.[3]

The primary objective of the NEAR mission was to inject a spacecraft into a 50-km orbit around the near-Earth asteroid Eros for the purpose of making scientific observations to determine its size, shape, mass, density, and spin rate. It could also determine the morphology and mineralogical composition of the surface.

Launched in February 1996, the NEAR mission used an Earth gravity-assist flyby in early 1998 to deliver the spacecraft to the asteroid Eros in January 1999. Orbital operations were to begin immediately following arrival and were planned to be about one year in duration. In the early part of its mission, June 1997, NEAR flew by the asteroid Mathilde. It found Mathilde to be composed of extremely dark material with numerous large impact craters, including one nearly six miles deep.

DSN support for the NEAR mission in 1996 and 1997 was conducted primarily on the 34-m HEF or BWG antennas, and the X-band uplinks and downlinks carrying telemetry, command, and ranging data were well within existing capabilities. Initial acquisition and a trajectory correction maneuver in March 1997 were accomplished by the DSN without incident.

During the critical phases of the mission and mission operations at Eros, NEAR required continuous tracking support (three 8-hour passes per day) from the 34-m stations, with occasional use of the 70-m antennas. At other periods during the cruise phase, the tracking support was reduced to one or two passes per day.

In preparation for an Earth swing-by maneuver in early 1998, tracking support for NEAR was increased to the level of three passes per day in December 1997.

### Mars Global Surveyor

Mars Global Surveyor (MGS) was the first mission in a new program of Mars exploration called the Mars Surveyor Program. It was also the first of NASA's new "faster, better, cheaper" family of missions. MGS was designed to deliver a single spacecraft to Mars for an extended orbital study of the surface, atmosphere, and gravitational and magnetic fields of the planet. A search for gravitational waves and a demonstration of Ka-band downlink communications technology was to be conducted during the flight to Mars. The spacecraft was to be launched during the November 1996 Mars opportunity, using a Delta launch vehicle with a PAM D upper stage. The transit time to Mars would be about ten months. MGS was to be the first U.S. spacecraft to orbit Mars since the Viking Orbiters twenty years before and the first to use aerobraking rather than propulsive maneuvers to adjust its orbit upon arrival. The use of aerobraking techniques had been demonstrated in mid-1993 during the final stages of the Magellan mission to Venus and was considered to be a promising technique for reducing the

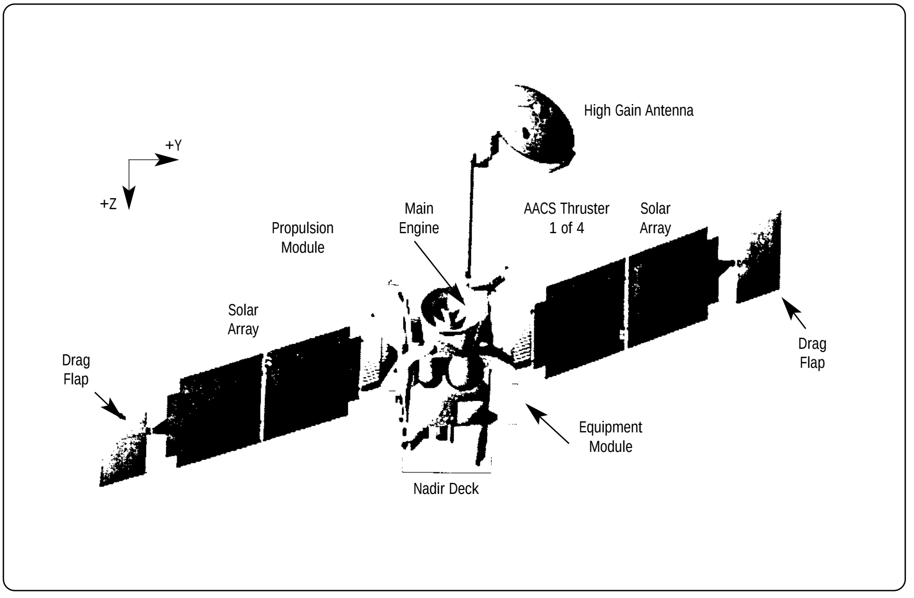


Figure 6-2. *Mars Global Surveyor* spacecraft in mapping configuration. The spacecraft was built and operated by Lockheed Martin Astronautics, JPL's industrial partner on the mission, in Denver, Colorado.

spacecraft fuel expended in circularizing the spacecraft orbit around a planet. Repetitive observations of the Mars surface and atmosphere were to be carried out from a nearly circular, low-altitude (378 km) orbit over a period of one Martian year (687 Earth days).

An overview of the major components of the spacecraft is shown in Figure 6-2.

Like the earlier *Mars Observer* spacecraft, MGS uplinks and downlinks were both on X-band, and it also carried a Ka-band downlink beacon as a new downlink technology demonstration. The downlink telemetry would employ Reed-Solomon and convolutional (K = 7, R = 1/2) encoding and would range from 10 bits per second to 32 kilobits per second for engineering data, and 4 kilosymbols per second to 85 kilosymbols per second for Reed-Solomon encoded science data. In coding terminology, a symbol is essentially a Reed-Solomon encoded data bit. The MGS spacecraft transmitted 250 encoded bits to represent every 218 bits of its raw science data, a ratio of 1.147 to 1.0.

The command uplink would operate at a nominal rate of 125 bits per second, although several other rates were available. Radio metric data consisting of two-way Doppler and sequential ranging data would be generated from the coherent X-band uplink and downlink carriers, and a noncoherent signal from the spacecraft's ultra-stable oscillator (USO) would be used to generate project data during the frequent occultation experiments.

The MGS mission required the tracking stations to be able to acquire the X-band downlink and achieve telemetry "in-lock" within five minutes of spacecraft view at the station, for data rates of 18.6 ksps or greater. Reacquisition of the telemetry signal following each Earth occultation during the mapping phase was to be accomplished within one minute of spacecraft view. These requirements, which posed some problems for the DSN, could not be solved before launch but were satisfied by the time the spacecraft reached Mars.

The DSN was required to deliver at least 95 percent of the science data transmitted from the spacecraft during the mapping phase to the Advanced Multimission Operations System (AMMOS) at JPL. Because the Mars Orbiter camera instrument made extensive use of data compression, the imaging science data could not tolerate significant gaps in the "packets" of telemetry data delivered by the DSN. This produced a further requirement on the DSN to deliver science data "packets" containing no more than one packet gap or error within 10,000 packets. This was equivalent to one error per 100 million bits ($1 \times 10^{-8}$) and would require some additional backup recording equipment in the GCF to meet the stringent requirement.

Following initial acquisition of the downlink signal after launch by the 26-m antenna at Canberra, the mission was to be supported by the 34-m HEF antennas, DSS 15, 45, and 65. The 34-m BWG antennas would also provide support as they became available in 1997. The 70-m antennas were to support the critical Mars Orbit Insertion sequence and to be available to support any other situations which were declared to be "critical" by the MGS flight operations manager.

DSN readiness to support the launch and cruise phase of the MGS mission was presented to a Telecommunications and Mission Operations Directorate (TMOD) Review Board in October 1996. For the first time, it was part of a broad-based review which included DSN and AMMOS as an integrated service of the TMOD. It was this integrated service (which included its multimission operators) that would be used by the MGS flight operations manager to conduct the mission after launch.

The DSN presentation satisfied the Review Board that it had verified telecommunications compatibility with the spacecraft, had adequately trained its operations personnel, had developed an Initial Acquisition Plan covering all available launch windows, and that all of the facilities necessary for launch and early cruise were in place. The uplink and downlink requirements for MGS were well within the capabilities of the DSN systems that had been implemented earlier under the SPC upgrade program. Because the issues of downlink acquisition time and telemetry data accountability were related to operations at Mars, they were not included in this review. The DSN, together with AMMOS, was ready to support the MGS launch.

At noon on 7 November 1996, *Mars Global Surveyor* lifted off launch pad 17A at Cape Canaveral Air Station, Florida, on a three-stage Delta II launch vehicle bound for Mars. All launch vehicle sequences were completed as planned and ended with separation from the spacecraft about 50 minutes after launch. An anomaly that occurred during deployment of the spacecraft solar panels was not a cause for concern at the time, since it was believed it could be corrected the following day. About 70 minutes after launch, just after the spacecraft came in view of Canberra, the X-band downlink was very quickly acquired, first by the 26-m antenna (DSS 46), and then by the 34-m HEF (DSS 45), using the offsets from DSS 46. The DSN settled into routine operations as MGS cruise support began.

Over the next several weeks, spacecraft engineers continued to evaluate various solutions to the problem created by the solar array anomaly, although it posed no immediate threat to the mission.

In January 1997, the spacecraft was turned to point its high-gain antenna toward Earth, and with a stronger downlink available, the spacecraft immediately began transmitting telemetry at the higher data rates. During a period of low activity in May, a program of observations directed to the search for gravitational waves was carried out. This was the long-awaited opportunity that had eluded the project investigators when the Galileo X-band mission failed. The high-stability X-band exciter and X-band uplink and downlink were key factors in reaching the sensitivity needed to detect the presence of gravity waves by their characteristic three-perturbation signature in the two-way Doppler data. There was no immediate answer to whether the observations revealed the presence of gravitational waves, since analyses of these data would take many months to complete.

Ka-band technology demonstration passes with DSS 15 and DSS 13 were conducted over a two-week period beginning on 21 July. The Ka-band downlink was received at DSS 13 in a coherent mode with the X-band uplink from DSS 15. After a period of good ranging data had been recorded, DSS 15 transferred its uplink to DSS 34 to generate comparative data over the Goldstone/Australia path.

In July, with the spacecraft rapidly approaching Mars, mission controllers and DSN operators engaged in several simulation exercises to prepare for orbital operations. During the simulations, the spacecraft radio transmitter was turned on and off over the course of a six-hour period to simulate three actual orbits. Because capturing the project data and acquiring the telemetry data under these rapidly changing conditions would be an operationally demanding task for the tracking station operators and project team, these simulations were used to familiarize them with the necessary operational procedures.

About three weeks before the actual MOI, the DSN team reviewed its state of readiness to support the rapidly approaching orbit insertion and orbital operations phase of the MGS mission. As in the Launch Readiness Review, the review included the status of the AMMOS as well as that of the DSN.

The DSN team presentation focused on the steps that had been taken to meet the telemetry delivery (data gaps) and acquisition (lock-up time) requirements that had been of concern to the DSN prior to launch. It was shown that the implementation of reliable network servers in the GCF and the correction of a known antenna-pointing anomaly at the BWG stations had accounted for most of the difference between actual measured performance of the DSN and the performance required by the MGS specifications. The remaining errors would be attributable to data gaps induced by downlink data rate changes on the spacecraft. Although lab measurements at JPL and past performance at the stations confirmed that telemetry lock-up time would meet the requirement, some uncertainty remained until the actual downlink became available and performance was verified under fully operational conditions. An operations support plan for the MOI sequence; availability of the necessary antennas, communications, and facilities; and a demonstrated level of crew training completed the DSN presentation. There were no outstanding issues or concerns. The DSN's Telecommunications and Mission Services (TMS) manager, John C. McKinney, assessed the status as Network-ready to support the Mars Orbit Insertion and Aerobraking events.

The DSN configuration used to support *Mars Global Surveyor* orbit insertion and orbital operations is shown in Figure 6-3.

The spacecraft executed the orbit insertion sequence perfectly, beginning with a 22-minute retro-engine burn on 11 September 1997, during the mutual view period of Canberra and Madrid. Twelve minutes after the start of the engine burn, the first Mars occultation occurred, providing the tracking station operators with their first opportunity to demonstrate the benefits of the simulated acquisition training. When the spacecraft emerged from behind the planet four minutes after the retro-engine burn had been com-

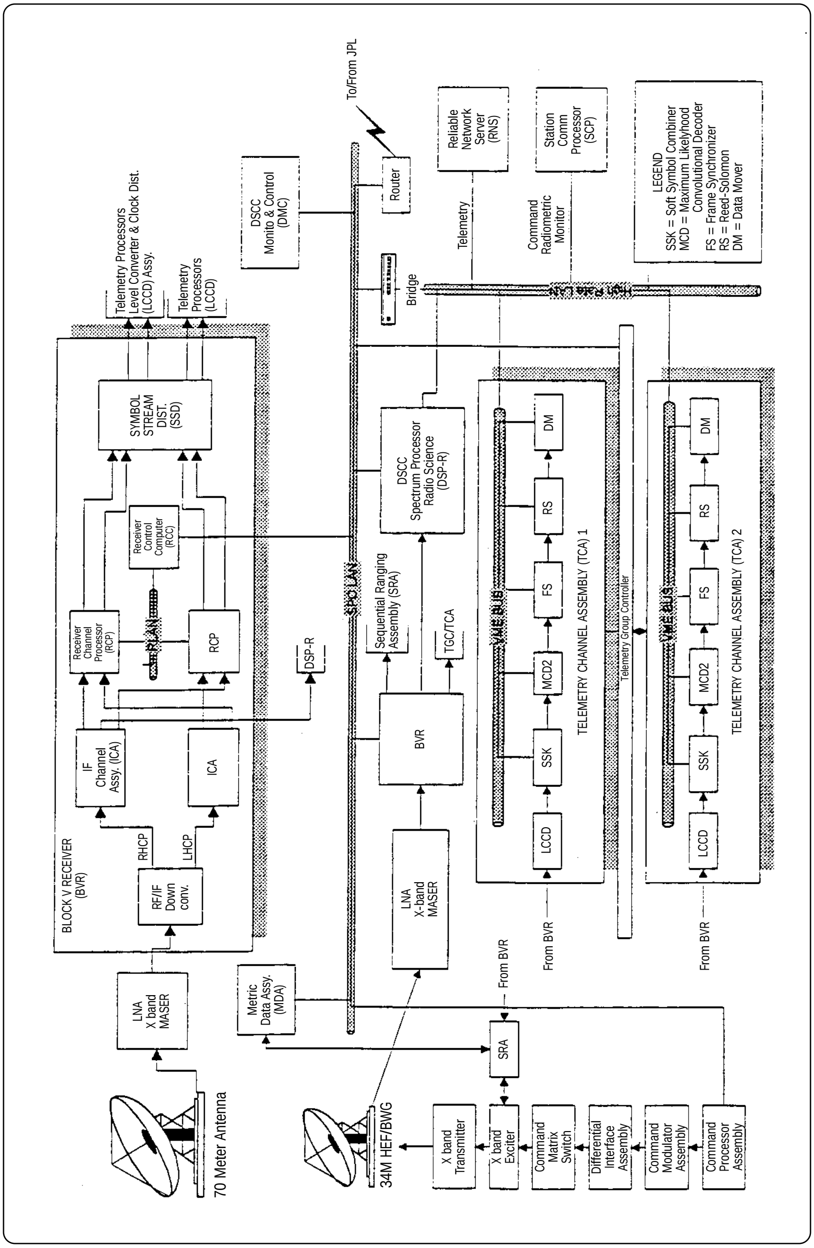


Figure 6-3. DSN configuration for *Mars Global Surveyor*. This was the standard DSN configuration for the Cassini Era and has been discussed earlier as part of the SPC upgrade task. It was used in various forms for all the missions in 1996 and 1997.

pleted, the downlink was acquired within seconds. Doppler data indicated that the spacecraft had entered a highly elliptical orbit within one minute of the intended 45-hour orbit. The spacecraft was about 250 km above the Martian surface (periapsis) and about 56,000 km above the surface at the farthest point (apoapsis).

A few days after the spacecraft began orbiting the planet, the spacecraft magnetometer detected the existence of a planet-wide magnetic field. This discovery was hailed by Vice President Gore as "another example of how NASA's commitment to faster, better, cheaper Mars exploration is going to answer many fundamental questions about the history and environment of our neighboring planet."

The first aerobraking maneuvers began with retro-engine burns at apoapsis on 17, 20, 22, and 24 September. As each periapsis passage began to take the spacecraft into the upper reaches of the Mars atmosphere, atmospheric drag provided additional aerobraking effect. While the orbit slowly decreased, data taking progressed to the point where the MGS Science Team was able to hold a press conference at JPL on 2 October to report their findings from all six science experiments. "The spacecraft and science instruments are operating magnificently," reported Dr. Arden Albee, the MGS project scientist at the California Institute of Technology, Pasadena, California. "The initial science data we've obtained from the walk-in phase of aerobraking are remarkable in their clarity, and the combined measurements from all of the instruments over the next two years are going to provide us with a fascinating new global view of the planet."

Suddenly, during the fifteenth periapsis passage on 6 October, significant movement was observed in the damaged solar array panel. On 12 October the orbit was temporarily raised to reduce the stress on the solar panel at each periapsis passage while the operations teams at JPL and Lockheed Martin Astronautics investigated this potentially alarming situation. Two weeks later, with the spacecraft in a 35-hour orbit and closest approach to the surface of 172 km, aerobraking was resumed at a much slower rate than before to avoid putting undue stress on the unlatched solar panel. This decision would extend the aerobraking phase by eight to twelve months and would change the final mapping orbit. However, it would not significantly affect the ability of MGS to accomplish its primary mission's science objectives.

Apart from the faulty solar panel, the spacecraft was operating perfectly, and with DSN support available from the BWG antennas, science data collection continued unabated. An image of the giant volcano Olympus Mons taken during this period is shown in Figure 6-4.

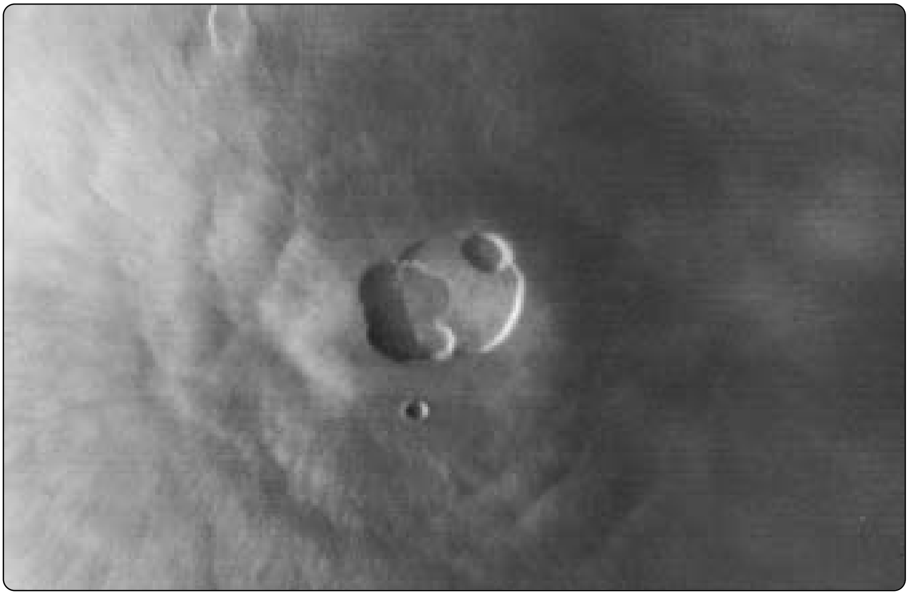

Figure 6-4. *Mars Global Surveyor* image of Olympus Mons. *Mars Global Surveyor* obtained this spectacular wide-angle view of Olympus Mons from an altitude of 900 km (500 mi) above the surface on its 263rd orbit around the planet on 25 April 1998. More than three times the height of Mt. Everest, this giant volcano is almost flat, with its flanks having a gentle slope of three to five degrees.

MGS completed its 100th orbit around Mars in January 1998. Assisted by the calm state of the Martian atmosphere, aerobraking operations were proceeding satisfactorily. The spacecraft had reached a 19-hour orbit around the planet, with a high point of about 28,000 km and a low point of about 120 km.

The target date for the start of mapping operations was March 1999, and it was hoped that the duration of the mapping phase would still be one Martian year. The DSN was providing support with the 34-m HEF antennas on a routine basis with typical downlink data rates of 2,000 bits per second for engineering and 21,333 symbols per second for playback of science data.[4]

### *Mars Pathfinder*

About one month after *Mars Global Surveyor* lifted off the launch pad at Canaveral Air Force Station bound for Mars, the second spacecraft in the Mars Discovery Program was launched from the same pad with the same destination, but with a different objective. *Mars Pathfinder* (MPF) was primarily an engineering demonstration of key technologies and concepts for eventual use in future missions to Mars employing scientific Landers. MPF also delivered a scientific instrument package to the surface of Mars to investigate the elemental composition of Martian rocks and soil and the structure of the Mars atmosphere, surface meteorology, and geology. In addition, MPF carried a free-ranging surface Rover, which was deployed from the Lander to conduct technology experiments and to serve as an instrument deployment mechanism. At launch, the mass of MPF was 890 kilograms, compared to 1,060 kilograms for MGS. MPF would arrive at Mars on 4 July 1997, seven months after launch, compared to 11 September 1997, ten months after launch, for MGS.

The MPF spacecraft comprised three major elements: the cruise vehicle, the deceleration systems, and the Lander vehicle that contained the Rover.[5]

The cruise vehicle provided the major spacecraft functions of power generation, propulsion, and attitude control prior to entry into the Martian atmosphere. The deceleration subsystem comprised an aeroshell, parachute, tether, retrorockets and inflatable airbags. The tetrahedral Lander structure enclosed the science instruments, the Rover, and the engineering subsystems necessary for cruise and surface operations. The radio transponder and transmitter, along with attitude control and data handling electronics and software, were also located on the Lander and were connected to the cruise stage via a detachable cable harness. The Lander structure was self-righting, with three side petals that opened to establish an upright configuration on the surface from which the Rover could be deployed. Power was provided by solar arrays mounted on the surface panels.

The MPF Lander with the Rover vehicle in a deployed configuration on the Mars surface is depicted in Figure 6-5.

The duration of the primary mission was defined to be 30 days beginning at the time of landing. Pathfinder requirements for tracking and data acquisition lay within current (1997) DSN capabilities, and the Telecommunicatons and Mission Services (TMS) manager Dennis M. Enari concluded that no special implementation was needed. Both uplink and downlink for MPF were on X-band and would be used for command, telemetry, and generation of radio metric Doppler and range data. There were no requirements for

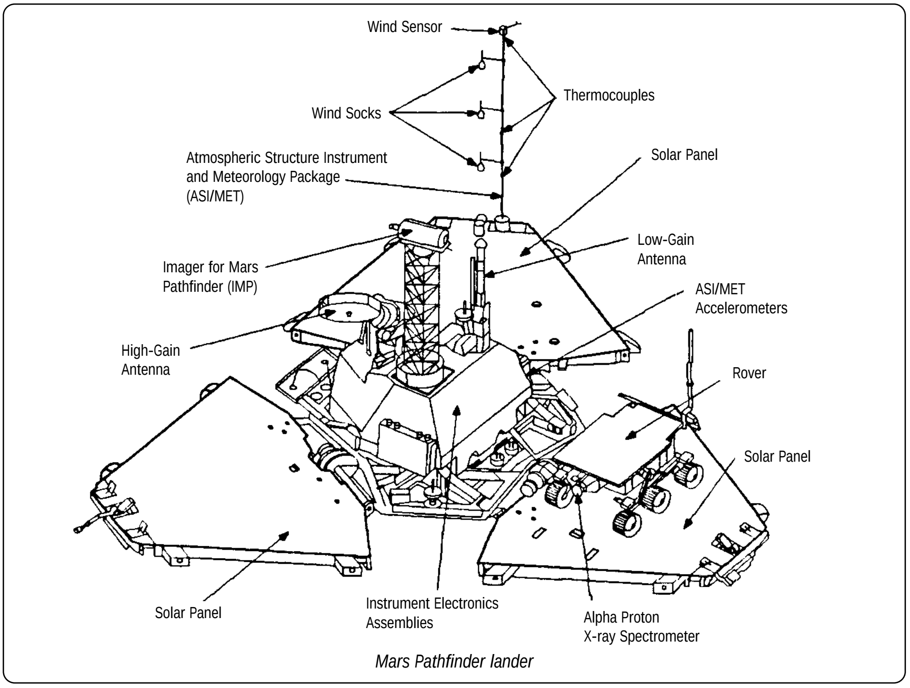


Figure 6-5. Pathfinder Lander deployed on the surface of Mars.

project observations, although the DSCC project equipment would be used to record open-loop spectral data from the X-band downlink during the rapid and critical entry, descent, and landing sequence. Descent Doppler profiles and key engineering telemetry data would be reconstructed from this data after the event. Telemetry data rates would range from 40 bits per second in the cruise phase to 22,120 bits per second during surface operations. All data would be convolutionally coded at either (R = 7, K = 1/2) or (R = 15, K = 1/6). There would be no uncoded data. Command data rates ranging from 7 to 500 bits per second would be used on the X-band uplink.

During the entry, descent, and landing phase, both the 70-m and the 34-m HEF antennas at Madrid would be tracking the MPF spacecraft simultaneously. At other times, the tracking support would be provided by the 34-m HEF and 34-m BWG antennas, with occasional use of the 70-m antennas for the downlink only. The 26-m antennas at DSS 46 and DSS 16 would provide support for the initial acquisition events only.

*Mars Pathfinder* blasted into space on 4 December 1996, the third day of its launch window. The launch, ascent, orbital injection, and spacecraft separation events were all normal. About 70 minutes after lift-off, the spacecraft made its first appearance over the Goldstone radio horizon. Stations DSS 16 and DSS 15 quickly locked up their receivers on the downlink signal and, less than two minutes later, began flowing telemetry data to the mission controllers at JPL. On the evidence of these data, the spacecraft team reported that all critical spacecraft systems, such as power, temperature, and attitude control, were performing well. "Everything looks really good and we're very happy," said Tony Spear, Pathfinder project manager at NASA's Jet Propulsion Laboratory.

An event of some significance to the DSN occurred on 18 January 1997 when the new Block 3 Maximum Likelihood Decoder (MCD3) was used for the first time to process live inflight data from DSS 15 Goldstone.

The MCD3 grew out of the technology that had been used by Statman in developing the Big Viterbi Decoder for the original Galileo X-band mission in 1989. Although that effort was dropped when the spacecraft high-gain antenna problem forced a redesign of the Galileo mission in 1991, the enhancement in downlink performance available from newer, more powerful convolutional codes remained viable. Although the encoding process in the spacecraft was a relatively simple process, the new codes required much bigger and extremely complex decoders in the DSN to take advantage of the improvement in performance. In the intervening years, DSN engineers had pursued the development of such a machine and, by the time of the MPF mission, were ready to demonstrate the first machine of its kind in a real, inflight situation.

In this demonstration, the MPF telemetry downlink consisted of a convolutionally coded (R = 15, K = 1/6) data stream, running at 4,070 bits per second. In light of the importance of this machine to later MGS, MPF, and Cassini mission support, its first successful demonstration under operational conditions was a matter of considerable satisfaction to the DSN.

The cruise phase passed quietly without the occurrence of any significant incidents. Spacecraft and science instrument status checks were made routinely, and several trajectory correction maneuvers were successfully executed. The DSN operations team carried out several rehearsals to improve proficiency in the procedures that would be used in July for the entry, descent, and landing sequence in July.

On 30 June, with all spacecraft systems in excellent operating condition and commanded by a sequence from its onboard computer, the MPF spacecraft began the entry, descent, and landing phase of its mission. On the morning of 4 July, an update of the MPF orbit based on the latest DSN Doppler and range data indicated that MPF was heading straight for the center of its predetermined 60-mile by 120-mile landing ellipse and would enter the upper atmosphere at an entry angle just 0.75 degrees less than its original design value of 14.2 degrees. A few hours later, at 10:07:25 a.m. Pacific time, 4 July 1997, the MPF spacecraft landed successfully on the surface of Mars, marking NASA's return to the surface of the Red Planet after more than twenty years. A low-power transmission from an independent antenna on one of the petals confirmed the landing and indicated that the craft had landed on its base petal in an upright position.

The first low-gain antenna transmission was received on schedule about four hours later. It contained preliminary information about the health of the Lander and Rover; the orientation of the spacecraft on the surface; the entry, descent, and landing; and the temperature and density of the Martian atmosphere. This was soon followed by a high-gain antenna transmission which contained the first images from the Lander. The next day, 5 July, after clearing a problem with the petal that the Rover needed as a ramp to reach the surface and rectifying a Rover-to-Lander communication link problem, the mission control team moved the Rover vehicle (named Sojourner) down the ramp under its own power and onto the Martian soil. Images of the Rover from the Lander and vice versa, plus engineering data from both, confirmed that both vehicles were in their proper positions and in good operating condition. With the downlink telemetry data rate set to 6,300 bps, science activities from the surface began in earnest.

During the first two weeks of surface operations, uplink and downlink communications were interrupted several times due to Lander computer resets that unexpectedly switched the low-gain and high-gain antennas, and to operational errors related to the timing of the limited duration downlink sessions. Once these initial problems were cleared up, the data rate was raised to 8,300 bps and the return of high-quality data from the MPF Lander became a matter of routine operation for the DSN. Downlink sessions with the Lander were of short duration, generally about ninety minutes, during which about 60 megabits of science and engineering data were returned. By the time MPF had completed its primary 30-day mission on 3 August, it had returned 1.2 gigabits of data, including 9,669 images of the Martian landscape.

The designers of the spacecraft and the mission had every reason to be proud of their efforts. "This mission demonstrated a reliable and low-cost system for placing science payloads on the surface of Mars," said Brian Muirhead, Mars Pathfinder project manager at JPL. "We've validated NASA's commitment to low-cost planetary exploration,

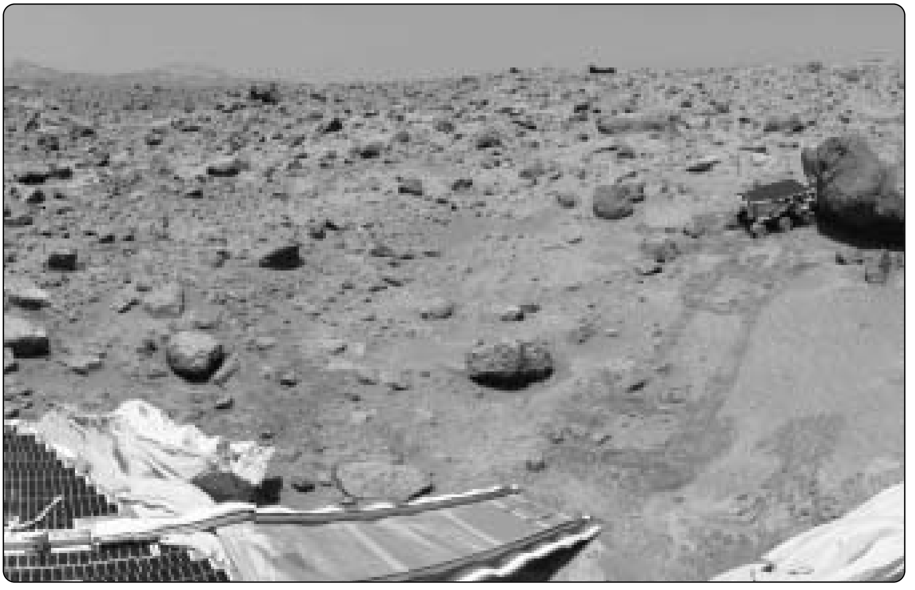

Figure 6-6. The MPF Lander camera views the Sojourner Rover in operation near Yogi Rock on the surface of Mars, July 1997.

shown the usefulness of sending microrovers to explore Mars, and obtained significant science data to help understand the structure and meteorology of the Martian atmosphere, and to understand the composition of the Martian rocks and soil."

The downlink telemetry data from Mars, delivered by the DSN stations to JPL in real time were subsequently processed into images by the MPF scientists and made available to the media and on the World Wide Web. The images returned from both Lander and Rover were remarkable indeed, but it was the robust, semi-autonomous Rover, Sojourner, that captured the imagination of the public. To accommodate the swell of public interest in following the mission via the World Wide Web, JPL engineers, in cooperation with several educational and commercial institutions, constructed twenty Pathfinder mirror sites. Together, these MPF sites recorded 565,902,373 hits worldwide during the period 1 July–4 August. The highest number occurred on 8 July, when a record 47 million hits were logged, more than twice the number received by the official Web site for the 1996 Olympic Games in Atlanta, Georgia.

A typical high-quality MPF image transmitted from Mars to Earth over the DSN telemetry downlink is shown in Figure 6-6. The inherent capability of the DSN downlink contributed to the remarkable detail observed in this and other MPF images.

Downlink communications with the Lander continued with no sign of trouble until 27 September, when DSS 15 at Goldstone was unable to detect the presence of a downlink at the scheduled transmission time. Declaration of a spacecraft emergency by the Pathfinder mission director authorized Enari to negotiate the release of the 70-m antennas from Galileo and MGS support to assist with DSN attempts to recover the MPF downlink. At the time, it was surmised that the downlink problems were most likely related to depletion of the spacecraft battery and uncertainties in the status of the onboard clock. While the spacecraft team investigated various scenarios to explain what might have happened to the spacecraft, the DSN went into emergency mode on a daily basis for all MPF passes.

While these downlink recovery efforts were going on, however, there was a great deal of excitement in the science community as the scientific results of the mission became available. A press release on 9 October 1997 reported that "Mars was appearing more like a planet that was very Earth-like in its infancy, with weathering processes and flowing water that created a variety of rock types, and a warmer atmosphere that generated clouds, winds, and seasonal cycles."

At an 8 October 1997 press briefing at JPL, Mars Pathfinder project scientist Dr. Matthew Golombek observed, "What the data are telling us is that the planet appears to have water-worn rock conglomerates, sand, and surface features that were created by liquid water. If," he added, "with more study, these rocks turn out to be made of composite materials, that would have required liquid water flowing on the surface to round the edges in pebbles we see on the surface or explain how they were embedded in larger rocks. That would be a very important finding."

Golombek also stressed the amount of differentiation—or heating, cooling, and recycling of crustal materials—that appeared to have taken place on Mars. "We're seeing a much greater degree of differentiation—the process by which heavier elements sink to the center of the planet while lighter elements rise to the surface—than we previously thought, and very clear evidence that liquid water was stable at one time in Mars'[s] past. Water, of course, is the very ingredient that is necessary to support life," he added, "and that leads to the $64,000 question: Are we alone in the universe? Did life ever develop on Mars? If so, what happened to it and, if not, why not?"

Despite the most intense efforts by the DSN and spacecraft controllers to detect the presence of a downlink, however weak or off-frequency it may have been, no downlink could be found. There was conjecture that, without the heat generated by the battery-powered transmissions, the spacecraft temperature would fall below its operating limits and the spacecraft computer that controlled the spacecraft transmission times would no longer operate correctly. Whatever the cause, the downlink was never recovered, and further efforts were discontinued in mid-October.

At the time of the last downlink, the Lander had operated for nearly 3 times its design lifetime of 30 days, and the Sojourner Rover had operated for 12 times its design lifetime of 7 days. After the 4 July landing, it returned 2.6 billion bits of data, which included more than 16,000 images from the Lander and 550 images from the Rover, as well as more than 15 chemical analyses of rocks and extensive data on winds and other weather factors. All MPF requirements of the DSN for telecommunications and data acquisition support had been fulfilled.

The cost of designing and building the Pathfinder had been $171 million; that of the Sojourner Rover, $25 million. Together, their combined costs would have been a mere round-off error in the $3 billion (1997 dollars) cost of NASA's previous mission to Mars, the Viking Landers in 1976. In that sense, the MPF mission had accomplished one of its primary objectives. As Brian Muirhead, Mars Pathfinder project manager at JPL, declared at the end of the mission, "This mission has demonstrated a reliable and low-cost system for placing science payloads on the surface of Mars. We've validated NASA's commitment to low-cost planetary exploration."

NASA seemed well satisfied. A few weeks later, NASA Administrator Daniel S. Goldin recognized the efforts of all involved with the mission in a formal press release: "I want to thank the many talented men and women at NASA for making the mission such a phenomenal success. It embodies the spirit of NASA and serves as a model for future missions that are faster, better, and cheaper. Today, NASA's Pathfinder team should take a bow, because America is giving them a standing ovation for a stellar performance."

At the same time that it was dealing with the highly visible Mars Pathfinder events described above, the DSN was also handling the arrival and aerobraking maneuvers of the *Mars Global Surveyor* and arrayed operations for the Galileo encounter with the Jupiter satellite Callisto. While these dramatic events were unfolding at JPL and around the Network, another deep space mission was being readied for launch at Cape Canaveral. The Cassini Saturn Orbiter with the Huygens Titan Probe had been successfully mated with the Titan IV/Centaur at the Cape Canaveral Air Force Station, and launch was planned for 13 October.

**Cassini**

The Cassini mission to Saturn and Titan was a cooperative endeavor by NASA, the European Space Agency (ESA), and the Italian Space Agency (ASI). Its genesis can be traced to the early 1980s, when the international science community agreed upon a combined Saturn Orbiter/Titan Probe mission as the next logical step in the exploration of the solar system, following the Galileo mission to Jupiter. It was seen as a follow-on mission to the brief reconnaissance of Saturn, which had been carried out by the *Pioneer 11* spacecraft in 1979 and the *Voyager 1* and *2* encounters of 1980 and 1981. It would be an enterprise that would span nearly thirty years from its initial vision to its completion in the year 2008.

The Cassini mission was designed to make a detailed scientific study of Saturn; its icy moons, magnetosphere, and rings; and the satellite Titan. Observations relative to the first four science objectives were to be made by twelve science instruments carried on an orbiting spacecraft (*Cassini*). The Titan observations would be made by six science instruments onboard a probe (Huygens), which would be carried to the vicinity of Saturn by *Cassini* before being released to descend to the surface of the satellite. In addition to these experiments, the DSN Project System would be used to conduct at least three gravitational wave searches en route to Saturn and to carry out numerous occultation experiments with the planet, moons, and rings during the orbital phase of the mission.

Scheduled for launch in October 1997 using a Titan IV/Centaur launch vehicle, the spacecraft would require a unique set of four gravity-assist maneuvers to arrive at Saturn almost seven years later, in July 2004. The gravity-assists would be provided by close flybys of Venus in April 1998 and June 1999. It would then fly by Earth in August 1999 and Jupiter in December 2000. The *Cassini* interplanetary trajectory with the four gravity-assist maneuvers is shown in Figure 6-7.

To reduce costs, the development of many mission operations capabilities was deferred until after launch. Except for the three gravitational wave experiments, there were no plans to acquire science data during the cruise phase or gravity-assist maneuvers. Spacecraft operations during the interplanetary cruise would be centralized at JPL. During the orbital phase of the mission, a system of distributed science operations would allow scientists to operate their instruments from their home institutions with the minimum interaction necessary to collect their data.

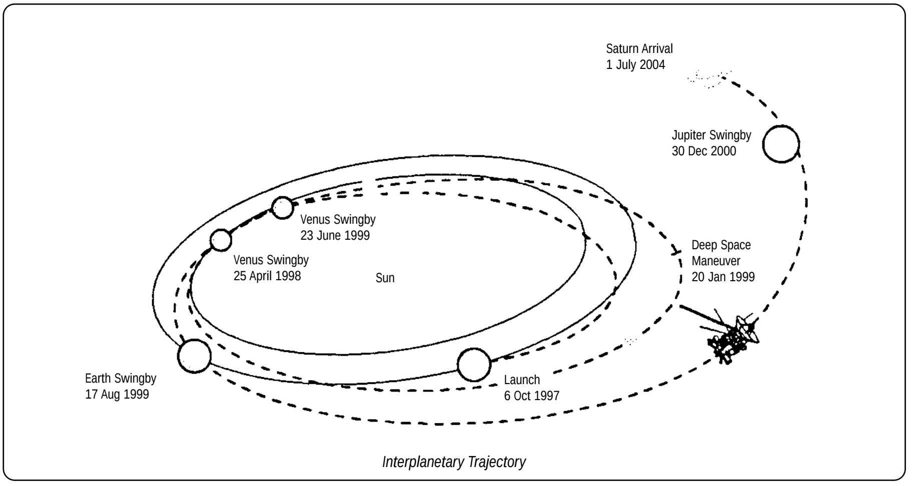


Figure 6-7. *Cassini* interplanetary trajectory.

*Cassini* was a three-axis-stabilized spacecraft, the main body of which was formed by a stack consisting of a lower equipment module, a propulsion module, an upper equipment module, and the HGA. The various science instruments were mounted on pallets and, together with the Huygens Probe and RTGs, were attached to the stack at appropriate points. The spacecraft contained twelve engineering subsystems in addition to its complement of twelve science instruments.

At launch, the combined weight of *Cassini*, the Huygens Probe, fuel, and the launch vehicle adaptor was 5,712 kilograms, making it the heaviest interplanetary spacecraft ever launched by NASA. More than half of the launch weight was contributed by the propellant needed for the 94-minute main engine burn that would inject *Cassini* into Saturn orbit. The spacecraft stood 6.8 meters high, with a maximum diameter of 4 meters due to the HGA. The major components of the spacecraft are identified in the diagram shown in Figure 6-8.

The design of the *Cassini* spacecraft was the end result of extensive tradeoff studies that considered cost, mass, reliability, the availability of hardware, and past experience. Moving parts were eliminated from the spacecraft wherever possible. Science instruments and the high-gain antenna, which replaced the deployable type of antenna used on *Galileo*, were permanently attached to the spacecraft, their pointing functions performed by rotation of the entire spacecraft. Tape recorders were replaced with solid-state recorders

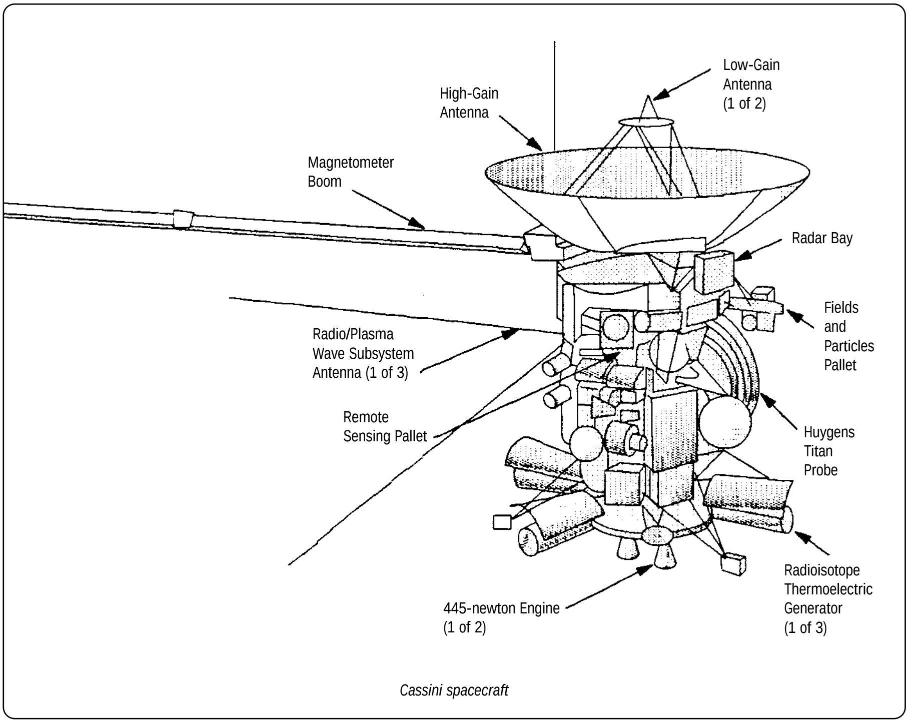


Figure 6-8. *Cassini* spacecraft with Huygens Probe.

and mechanical gyroscopes were replaced with hemispherical resonator gyros. The high-gain antenna would be used for the short-duration (2.5 hours), S-band radio-relay link between *Cassini* and the Huygens Probe, as well as for the permanent radio link between *Cassini* and Earth.

Uplink and downlink communications on X-band were provided by the Radio Frequency Subsystem. A Radio Frequency Instrument Subsystem provided unmodulated RF carriers on the Ka-band and S-band for project experiments only during the cruise and orbital phases. The X-band uplink carried command data in the range 7.8 bps to 500 bps and sequential ranging modulation. The Ka-band uplink was unmodulated. Both Radio Frequency Subsystems included redundant Deep Space Transponders (DSTs). Originally developed as a joint DSN/Flight project task at JPL in 1990 for use on X-band only, the DST was first flown on the NEAR and *Mars Pathfinder* spacecraft in 1996.[6] It was later upgraded to include Ka-band and was flown for the first time in that configuration on *Cassini*.[7]

The X-band downlink carried telemetry data with a wide range of data rates, from 5 bps to 249 kilobits per second. The telemetry data was encoded with Reed-Solomon (255, 223) coding concatenated with Viterbi (7, 1/2) or (15, 1/6) coding prior to transmission. It could also be transmitted in uncoded form. In addition to telemetry, the downlink carried ranging modulation.

The versatile design of the DST provided X-band, Ka-band and S-band downlinks that could be either coherent or noncoherent with the X-band uplink. The Ka-band downlink could be coherent with, or noncoherent with, the Ka-band uplink. This allowed the downlinks to be optimized for the various project investigations under a wide range of conditions.

The Antenna Subsystem included the 4-meter-diameter, narrow-beam-width HGA that was designed for transmitting and receiving on all four communication bands, and two wide-beam-width, low-gain antennas that could receive and transmit on X-band only.

Working with Cassini mission designers, the Telecommunications and Mission Services (TMS) manager, Ronald L. Gillette, negotiated tracking and data acquisition services for the mission that generally fell within the existing (1997) or planned (2002) capability of the Network. The 70-m, 34-m BWG, and 34-m HEF subnets would be required singly or arrayed at various times during the mission. The initial acquisition and early cruise requirements, when the spacecraft would be using its low-gain antennas, would be met without the need for any new implementation. By 2001, however, the 20-kW X-band uplinks on the 34-m HEF antennas would not provide adequate uplink margin for commanding and X-band transmitters, and exciters would be needed on the three 70-m antennas. The DSN agreed to provide this new capability. The DSN also agreed to provide a Ka-band uplink and downlink at DSS 25 for the project experiments, particularly the first gravitational wave experiment of 40 days' duration in 2001. Where the research and development installation at DSS 13 had been equipped with an 80-watt transmitter, this first fully operational Ka-band capability in the Network would have a 4-kW transmitter and provide simultaneous X-band and Ka-band downlink capability.

A new and innovative approach to orbital operations planning was expected to effect economies in the scale of DSN coverage required to support this critical phase of the mission. For the purposes of operational simplicity, DSN coverage was classified into two categories: "high activity," when science opportunities would be most intensive, such as targeted satellite flybys and Saturn periapses; and "low activity," when fewer science opportunities would permit lower data return volume. The science community had agreed that a data volume return of 4.0 gigabits per day for high activity periods and 1.0 gigabit per day for low activity periods would be adequate to accomplish their science objectives. Because Saturn would be above the plane of the ecliptic during the period of orbital operations (2004–08), the daily view periods for the DSN antennas in the southern hemisphere would be of shorter duration, and the received downlink signal-to-noise ratio about 1.5 dB less, than they would be for the DSN antennas in the Northern Hemisphere. For this reason, the DSN agreed to provide coverage, most of the time, for antennas in the Northern Hemisphere, Goldstone, and Madrid. High-activity data return would be accommodated by the 70-m antennas and 70-m/34-m arrayed antennas in the Northern Hemisphere. Low-activity periods would be covered by the 34-m Northern Hemisphere antennas or the 70-m and 34-m Southern Hemisphere antennas, if necessary.

The sustainable data rates on the X-band downlink during Saturn orbital operations also depended on the position of Earth in its orbit around the Sun and on the change in elevation of the spacecraft as it made its daily pass over the tracking station. When all these variables were considered, it was estimated that the downlink data rates would vary over the range 14 to 166 kilobits per second.

In a joint effort to reduce the complexity and cost of daily orbital operations, the factors just described were used by the DSN and Cassini mission planners to develop a data return strategy based on an average pass length of about 9 hours. This strategy optimized the downlink capability with the defined science activity period while limiting the data rate changes on the telemetry downlink to two or three per station pass. Once developed, each strategy would remain in effect for a fixed period, such as 90 days, during which time data rates and pass lengths would not be changed. This arrangement promised significant economies in mission planning and operations effort for both DSN and the Cassini projects.

After the White House gave approval to proceed, *Cassini* was launched without incident from Cape Canaveral, Florida, on 15 October 1997. White House approval to launch was required by presidential directive due to the use of RTG units to power the *Cassini* spacecraft. This matter had been the subject of a number of environmental protest demonstrations at Cape Canaveral in the weeks immediately preceding launch.

The Titan IV/B and Centaur Launch Vehicle functioned perfectly. "Right on the money," observed Cassini program manager Richard J. Spehalski. The sequence of post-launch events, including initial acquisition of the downlink by Canberra stations DSS 46 and DSS 45, was executed precisely as planned. First reports from the Cassini mission controllers indicated that the angular deviation of the trajectory from its design value was insignificant at better than 0.004 degrees. Mission plans had called for an expected adjustment in the post-launch trajectory of 26 meters per second, but flight data derived from the DSN radio metric data in the first few hours of two-way tracking showed that a correction of only one or two meters per second would be necessary to correct for the small injection error. Early DSN telemetry from CDSCC also showed that all subsystems on the spacecraft, including the solid-state recorder, were operating normally. "I can't recall a launch as perfect as this one," said Cassini mission director Chris Jones; "everything we see is within predictions, with no failures."

With the spacecraft high-gain antenna pointed toward the Sun and the X-band uplink and downlink established through the low-gain antennas, the DSN began the first 30 days of continuous tracking on the 34-m antenna subnet at the rate of 21 passes per week. During this time, mission controllers took advantage of the high data rate (14.2 kbps) available on the downlink, due to the short spacecraft-to-Earth range and the relatively quiescent (no science) state of the spacecraft, to carry out a series of engineering and science instrument maintenance activities. These activities included a checkout of the Huygens Probe about one week after launch. Because of the near-perfect post-launch injection conditions, the first trajectory correction maneuver on 9 November required only a 2.7-meters-per-second adjustment in spacecraft velocity to fine-tune its flight path. Real-time telemetry at 948 bps from DSS 54 allowed the spacecraft controllers to observe the 34.6-second main-engine burn in progress and provided reassuring evidence that this critical subsystem was functioning correctly.

By early January 1998, the *Cassini* flight team had completed all spacecraft activities planned for the early phase of the mission. Onboard software, stored in the command and data subsystem, had been directing spacecraft activities as planned, and the spacecraft thrusters were maintaining the spacecraft in its correct attitude in space. For the next 14 months, *Cassini* would fly with the HGA facing the Sun to shield the spacecraft from the intense solar radiation characteristic of the inner solar system. Throughout this period, the uplinks and downlinks with the DSN would be maintained through either of the two low-gain antennas, depending on the relative geometry of Earth, the Sun, and the spacecraft. Downlink data rates and weekly DSN tracking schedules were adjusted to meet the predefined, returned-data volume requirements. With all its subsystems working perfectly, and periodic instrument maintenance and spacecraft housekeeping activities dominating its routine schedule, *Cassini* moved steadily around its orbit toward an appointment with Venus on 26 April 1998, the first milestone on its seven-year voyage to Saturn.[8]

## EARTH-ORBITING MISSIONS

### General

By 1997, almost two-thirds of the missions that composed the total DSN mission set were missions of the Earth-orbital type. These are listed in the mission set for the Cassini Era, shown in Figure 6-1. Together with the Deep Space missions, these accounted for a Network operations load of 30 to 35 mission events being handled by the NOCC in a typical 24-hour period in 1997. In addition to the real-time mission events, a typical operations day for the NOCC would include two to five data playback sessions with the complexes.

Some of these spacecraft, like the Solar Heliospheric Observatory (Soho), Polar, Wind, and Geotail, were part of the continuing International Solar and Terrestrial Physics (ISTP) program and had been supported by the DSN for several years. Others, like Hotbird, were supported by the DSN only for the launch and early orbit period, a few days at most. Some were technology satellites; others were communications satellites; and some were solely for scientific purposes. Except for the cooperative Space VLBI mission HALCA and the reimbursable ESA mission Hotbird, all were NASA missions. However, the cooperative and reimbursable options for DSN support of future, non-NASA missions remained open. There were a number of other NASA missions, not listed in this set, for which the DSN assumed responsibility for providing tracking support in the event of a spacecraft emergency. Appropriate authorities and procedures to invoke support of this kind were permanently in place in the NOCC.

Spacecraft in low-Earth orbit (apogee less than 12,000 km) were supported on the 26-m or 34-m antennas, depending on their requirements for downlink data reception and handling. Those in high-Earth orbit usually required 34-m HEF or 34-m BWG antennas.

The HALCA spacecraft was a special case that warrants further discussion because of the new technology associated with its entry into the DSN. It was developed for the Japanese VLBI Space Observatory Program (VSOP) and was known by that name prior to its actual launch. Following a successful launch in February 1997, it became HALCA and participated in an international cooperative Space VLBI program for which the DSN provided some of the Earth-based antenna support.

## Space VLBI Observatory Program

The Space Very Long Baseline Interferometry (SVLBI) program was a two-mission, cooperative venture among NASA, Japan's Institute of Space and Astronautical Sciences (ISAS), and the Russian Astro Space Center (ASC). NASA participated in both missions with funding for the DSN; the National Radio Astronomy Observatory (NRAO) Very Long Baseline Array at Socorro, New Mexico; and the NRAO tracking station at Green Bank, West Virginia.

As early as 1983, Gerry S. Levy and his JPL associates had shown that the resolution of an array of Earth-based VLBI antennas could be greatly increased by means of a special spacecraft which would act as an extension of the Earth-based "radio baseline."[9] The SVLBI program applied and extended these basic ideas to improve the resolution of radio-astronomy images of celestial radio sources by extending the use of VLBI technology into space. The SVLBI missions therefore had a space component and a ground component, both of which heavily involved the DSN.

DSN involvement in the space component of the SVLBI project included the implementation of a new subnetwork of 11-meter antennas with Ku-band uplink and downlink capability. This effort is described later in this chapter. DSN participation in the ground component of SVLBI as a co-observer with the DSN 70-meter antennas is discussed in the Radio Astronomy section of this book.

The space component of the SVLBI program was to consist of two spacecraft: the VSOP (VLBI *Space Observatory Program*), provided by ISAS and launched in 1997, and the *RadioAstron*, provided by ASC and due to be launched several years later. Each spacecraft would carry a radio-telescope antenna and suitable receiving equipment for making radio-astronomy observations from a high-Earth orbit. The DSN's 11-meter antennas would provide continuous tracking support to supplement the limited tracking resources of the other participants in the program.

The VSOP antenna was capable of receiving signals in the three standard radio astronomy bands, L-band (1.6 GHz), C-band (5.0 GHz), and Ku-band (22 GHz). The digitized radio astronomy data, together with time synchronization signals, was to be transmitted to Earth over a Ku-band downlink at 128 Mbps. A Ku-band uplink carried time and frequency reference signals derived from a Hydrogen-maser at the Earth-based receiving stations to the spacecraft for use as a frequency reference. Spacecraft command and control functions and generation of radio metric tracking data used an S-band uplink and downlink that was completely independent of the Ku-band link. These functions were exercised from the Kagoshima Control Center and were not part of the DSN responsibility.

The VSOP spacecraft was successfully launched on 12 February 1997, on the then-new ISAS Mark-V launch vehicle, from the Kagoshima Space Center in Japan.[10] The satellite was renamed HALCA after launch. Following initial acquisition of the S-band downlink by the 26-m station at Goldstone, the Ku-band uplinks and downlinks were activated and communications were established with the 11-meter subnet consisting of DSS 23 (Goldstone), DSS 33 (Canberra), and DSS 53 (Madrid). Three perigee-raise maneuvers, done from 15 to 21 February, were used to place HALCA in a high elliptical orbit with an apogee of 21,400 km, perigee of 560 km, and orbit period of 6.3 hours. This high elliptical orbit had in inclination of 31 degrees (the latitude of the Kagoshima Space Center) and would enable VLBI observations on baselines up to three times longer than those achievable with Earth-based antennas. First interference fringes between HALCA and ground telescopes were found at the Mitaka, Japan, correlator in May, and at the Penticton, Canada, and Socorro, New Mexico, correlators in June 1997.

Tracking station passes varied in length from 10 minutes to as much as 5 hours, depending on the position of the spacecraft in its orbit at the time of the station pass. The short-period orbit provided two or three passes per day at each complex. The DSN was not required to perform any processing of the downlink data. It was simply recorded on special wide-band VLBI-compatible tapes and shipped to designated locations in the United States, Japan, and Canada. Special wide-band correlators at these centers processed the spacecraft observations together with corresponding data from the ground observatories, including the DSN 70-meter antennas, to produce the desired images of celestial radio sources.

## THE NETWORK

### Complexes and Antennas

By 1997, when the Cassini Era became a reality in the DSN, the total number of antennas operated by the DSN around the globe had increased to twenty-four, twelve at Goldstone and six at each of the Madrid and Canberra Complexes. The DSN also engaged in spacecraft mission operations with many other institutions around the world, each of which had one or more antennas of its own.

The sites of the DSN antennas and Signal Processing Centers were identified according to their geographical location, as shown in Figure 6-9. The sites of related antennas such as Weilheim, Germany; Usuda, Japan; and Parkes, Australia, were identified in the same manner.

It was convenient to describe the Network in terms of several subnets according to the metric diameter of the antennas composing it. There were a 70-meter subnet, two 34-m subnets, a 26-m subnet, an 11-m subnet, and several unique antennas such as DSS 13 and DSS 17 at Goldstone. An inventory of antennas in the DSN in 1997 is given in Figures 6-10, 6-11, and 6-12 for the Goldstone, Canberra, and Madrid complexes, respectively.

These tables show the various uplinks and downlinks that were available in 1997 to support space operations on each of the antennas. Comprehensive though this listing was, substantial additions were planned for it in the immediate future.

**Location Identifier for DSN and Related Sites**

| Number Range | Geographic Description and Position* |
|---|---|
| 00–29 | JPL/Goldstone and the VLA, Socorro, NM |
| 30–49 | Pacific Basin: Between L = 180 and L = 270 |
| 50–69 | European Basin: Between L = 345 and L = 90 |
| 70–89 | Atlantic Basin: Between L = 270 and L = 345 |
| 90–99 | Miscellaneous |
| 100–999 | GPS and Future Use |

*Note: L = Longitude in degrees, measured east from zero longitude.

Figure 6-9. Location identifiers for DSN and related sites.

**Goldstone Deep Space Communications Complex, 1997**

| DSS | Diam., Type | Uplinks | Downlinks | Operational |
|---|---|---|---|---|
| 12 | 34 m, STD | none | none | Decom’d. 2/96 |
| 13 | 34 m, BWG, R&D | S, X, Ka | S, X, Ka, Ku | 6/90 |
| 14 | 70 m | S | S, X | 64 m/70 m, 5/88 |
| 15 | 34 m, HEF | X | S, X | 8/84 |
| 16 | 26 m | S | S | 1/67 |
| 23 | 11 m, OVLBI | X | X, Ku | 2/96 |
| 24 | 34 m, BWG | X, S | S, X | 2/95 |
| 25 | 34 m, BWG | S, X | S, X, Ka | 8/96 |
| 26 | 34 m, BWG | X | X | 8/96 |
| 27 | 34 m, BWG, HS | S | S | 7/95 |
| 28 | 34 m, BWG, HS | S | S | 10/00 |

Figure 6-10. Goldstone Deep Space Communications Complex, 1997.

**Canberra Deep Space Communications Complex: 1997**

| DSS | Diam., Type | Uplinks | Downlinks | Operational |
|---|---|---|---|---|
| 33 | 11 m, OVLBI | X, Ku | X, Ku | 6/96 |
| 34 | 34 m, BWG | X | S, X | 11/96 |
| 42 | 34 m, STD | S | S, X | Decom’d. 12/99 |
| 43 | 70 m | S | S, X | 9/87 |
| 45 | 34 m, HEF | X | S, X | 12/84 |
| 46 | 26 m | S | S | 12/83 |

Figure 6-11. Canberra Deep Space Communications Complex, 1997.

**Madrid Deep Space Communications Complex, 1997**

| DSS | Diam., Type | Uplinks | Downlinks | Operational |
|---|---|---|---|---|
| 53 | 11 m, OVLBI | X, Ku | X, Ku | 6/96 |
| 54 | 34 m, BWG | X | S, X | 10/97 |
| 61 | 34 m, STD | S | S, X | Decom'd. 12/99 |
| 63 | 70 m | S | S/X | 64 m/70 m, 7/87 |
| 65 | 34 m, HEF | X | S/X | 4/87 |
| 66 | 26 m | S | S | 12/84 |

Figure 6-12. Madrid Deep Space Communications Complex, 1997.

The 70-m subnet would be provided with X-band uplinks for first use with *Cassini*, beginning with DSS 14 in 2000. Already, plans were being made to install an X-/Ka-band dichroic plate on the DSS 25 BWG antenna. This would be the first step in providing an operational Ka-band downlink for use on the Deep Space-1 mission and for project use with *Cassini* in 2000. The DSS 26 BWG antenna was being modified to demonstrate the more stringent antenna pointing capability required for Ka-band operation.

Driven by the need to reduce maintenance and operations costs, the closure of the 26-m subnet by the end of Fiscal Year 2001 had been under consideration since 1996. Several alternatives, including the automation of routine telemetry, command, and monitoring functions, the transfer of low-Earth-orbiting spacecraft to NASA's Wallops Island facility, and eventually to a commercial ground network, were being actively pursued in 1997.

Ways of making more effective use of DSN antenna time were demonstrated in several areas in 1996 and 1997. The "Multiple Spacecraft Per Antenna" concept was demonstrated effectively at Goldstone in September 1997 with the successful tracking of *Mars Global Surveyor* and *Mars Pathfinder* from a single antenna. Both spacecraft were at Mars and both lay within the beamwidth of a single 34-m BWG antenna (0.063 degrees at X-band). Several hundred commands were transmitted to each spacecraft, and good telemetry and two-way Doppler was obtained from each spacecraft. The operational advantages of this mode of operation were clearly demonstrated, particularly those related to switching the uplink from one frequency to another, and subsequent acquisition of individual spacecraft receivers. The DSN planned to develop this technique for future use as the Mars Exploration initiative would provide more opportunities for effecting economy in usage of DSN antennas.

For many years, it had been the practice to make regular, biweekly Earth motion and clock synchronization measurements between complexes by using two 70-m antennas simultaneously to observe a celestial radio source. Comparison of time off-sets in the observables provided a measure of the differences in time and frequency between the complexes. In 1997, with the addition of updated VLBI equipment and precision data from GPS receivers at the complexes, it became possible to accomplish the same biweekly measurements with two 34-m HEF antennas rather than two 70-m antennas.

In November 1997, the Future Programs Council at JPL heard a briefing on the future of deep space communications. The scope of the briefing included optical as well as conventional radio communications, but in the context of existing DSN antennas, it recommended that "to meet the increased needs of a growing mission set, NASA should rapidly deploy Ka-band capability throughout the existing DSN as a low[-]cost path which would allow future missions to double their data return while cutting their (antenna) contact time in half."

In time, by 1997, that statement seemed to indicate the direction of future development for antennas in the Network.

### Ka-band Downlink

Along with design concepts for beam waveguide antennas, the advantages of Ka-band communication links and the application of these ideas to future uplinks and downlinks for the DSN were discussed by Joel G. Smith, Robert C. Clauss, and James W. Layland in three companion reports in 1987.[11] These studies showed that a spacecraft-to-Earth downlink on Ka-band (32 GHz) could carry telemetry data at 3 to 10 times the data rate possible with an X-band downlink, given the same spacecraft transmitter weight, antenna size, and power requirements. This enhancement in downlink performance derived from increased antenna gain at higher frequencies (shorter wavelengths), but was reduced somewhat by other factors such as atmospheric and antenna losses and susceptibility to wet or foggy weather. A more indepth study of the tradeoffs associated with Ka-band operation in the DSN was carried out in 1988. This study described a scenario for establishing Ka-band as the primary Deep Space communications frequency of the future and proposed a baseline plan for reaching that goal.[12]

As the first two steps toward realization of Ka-band communication links in the future DSN, it was proposed that a Ka-band receiving capability should be added to the new research and development beam-waveguide antenna being built at DSS 13, and that a Ka-band beacon experiment (KABLE) should be planned for the *Mars Observer* spacecraft due to be launched to Mars in September 1992.[13]

This methodology had been used to introduce the X-band into the Network in 1973 as an S-/X-band experiment on the *Mariner 10* missions to Venus and Mercury. The Ka-band transponder for the *Mars Observer* spacecraft was the first step in a parallel development plan for spacecraft device and component technology proposed by Arthur L. Riley.[14]

The BWG antenna at DSS 13 was completed by mid-1990, as described in the preceding chapter, and its Ka-band capability was evaluated over the period July 1990 through January 1991.[15] The microwave feed package used on this antenna for KABLE consisted of an X/Ka-band dichroic plate and two low-noise amplifiers (LNAs), one for X-band and one for Ka-band. While the X-band LNA used a simple high-electron mobility transistor (HEMT) to achieve a system temperature of 37 kelvin, the ultra-LNA for Ka-band required the development of JPL's first Ka-band cavity maser to achieve a system temperature of 5 kelvin.[16] The Ka-band and X-band downlink signals, amplified by the LNAs, were converted to intermediate frequency and delivered to separate digital Advanced Receivers (ARX) for tracking, demodulation, and delivery to the telemetry decoders. A data-handling terminal carried out the telemetry recording and delivery tasks. Of the two advanced receivers, one was the unit that was being developed for the Galileo application in the DGT; the other was specially built for use at DSS 13 and would remain at the station. A special Doppler tuner was required for this unit to handle the Doppler jerk (rate of acceleration) expected on the Ka-band downlink when MGS would be in orbit around Mars.

The *Mars Observer* spacecraft was equipped with a special 33-milliwatt Ka-band transmitter and used the concave surface of the subreflector on the spacecraft's high-gain antenna as an antenna for the Ka-band downlink. To keep the Ka-band downlink coherent with the X-band uplink and downlink, its frequency, 33.66 GHz, was obtained by simply multiplying the X-band downlink frequency (8.4150 GHz) by four. Telemetry and ranging modulation were provided on both downlinks. At this time, fiber-optic cables were being introduced for intra-site communications and transmission of highly stable reference and timing signals between antennas on each complex. Full advantage was taken of this new facility to connect DSS 13 to the SPC 10 Control Room some 20 miles away, where the existing ranging and Doppler equipment was located.

The major objectives for KABLE included a telemetry demonstration, a ranging demonstration, and a tracking experiment. The telemetry demonstration would prove the feasibility of a telemetry link at Ka-band by collecting a minimum of one million bits of data, at 250 bits per second, with minimal errors. The ranging demonstration would follow the telemetry demonstration and illustrate the correct demodulation of DSN ranging codes at Ka-band. The tracking experiment would develop a database of Ka-band downlink statistics including weather, system noise, temperature, and antenna performance for use in the future development of Ka-band capability in the Network.

By an unfortunate coincidence, the telemetry demonstration took place during some of the worst weather conditions ever experienced in the Goldstone area. Heavy rains and dense fog were daily occurrences. This type of weather has a major degradation effect on Ka-band link performance and proved to be a limiting factor in reaching the data collection goal for telemetry. Although the ranging demonstration was limited to two passes only, due to various equipment problems and to the weather, it yielded a sufficient number of good ranging points for favorable comparison with theoretical performance. Equipment problems and bad weather also limited the amount of tracking data that was gathered. Nevertheless, sufficient Ka-band tracking data was retrieved to show a potential improvement of 4 to 7 dB over X-band performance under equivalent conditions.

Ironically, on 21 August 1993, just when the weather was improving and the equipment problems were being resolved, uplink and downlink communications with the *Mars Observer* spacecraft were lost. Later investigations led to the conclusion that the spacecraft had been destroyed during the engine pressurization sequence prior to the maneuver for Mars orbit insertion.

Despite its abrupt ending, sufficient data was obtained to declare the KABLE effort partially successful. The data that had been collected was thoroughly analyzed, and it ultimately provided a strong justification for a repeat experiment as soon as another opportunity presented itself.[17]

That opportunity would not be long in coming. In November 1996, when the *Mars Global Surveyor* spacecraft was launched on a mission similar to that of the ill-fated *Mars Observer*, it carried with it a much-improved version of the original Ka-band technology experiment called KABLE-II. Although KABLE-II was identical in concept to the earlier experiment, it benefited from several changes to the spacecraft and ground elements of the link. The Ka-band transmitter power had been increased to approximately 1 watt, and a change had been made to the way in which the frequency of the downlink Ka-band signal was derived in the spacecraft transponder. This change effectively placed the downlink signal frequency in the center of the receiving pass-band, rather than to one side of it, as was the case in Kable-I. Since the microwave components in the DSS 13 BWG antenna, particularly the dichroic plate, were optimized to receive at this band-center frequency, substantial loss in the downlink signal margin was avoided. At DSS 13, a new seven-element Ka-band array feed was used to receive the downlink and point the 34-m antenna with millidegree precision; Block V receivers replaced the earlier ARX developmental versions; and numerous other improvements related to operational reliability were made.

When the MGS spacecraft was pointed to Earth in mid-January 1997, strong signals were immediately received at DSS 13 and simultaneous X-/Ka-band tracking was carried out on six occasions thereafter. The array feed tracked the spacecraft within 1 millidegree in angle, and both carriers were tracked simultaneously to generate Doppler data by an experimental tone-tracker. Measurements were in good agreement with theory. The telemetry experiment began in February with an improved low-noise tracking feed which not only incorporated a multimode coupler to generate pointing error signals for driving the antenna pointing system, but also was cooled to reduce the system noise temperature.

On 21 March, the KABLE-II experimenters reported that a major objective had been successfully accomplished. Telemetry data received over the 1 watt, Ka-band link at 2 kbps had been compared bit-by-bit with data received over the 25-watt X-band downlink. All 12 million contiguous bits were in agreement. There were no errors. This event marked the first error-free telemetry reception at Ka-band in the DSN.

At this time, the Ka-band array feed, which had been replaced by the multimode-coupler feed at DSS 13, was installed and tested on the DSS 14 antenna in preparation for the start of Ka-band efficiency tests of the 70-m antenna in May. This capability would be needed for Cassini in the years ahead.

In mid-April, real-time telemetry data received from MGS over the Ka-band and the X-band links was presented to the MGS project operations team at JPL for evaluation. Dual-frequency tracking and ranging measurements were also made at this time. The experimental Ka-band downlink was received at DSS 13, while an operational X-band uplink and downlink was maintained at DSS 15. Both downlinks had been converted to 300-MHz IF frequency and transferred over fiber-optic circuits to SPC 10 for telemetry and radio-metric data processing and transmission to JPL.

The KABLE-II telemetry demonstrations with MGS at DSS 13 continued as scheduled through 8 May 1997. The successful demonstrations of Ka-band technology occasioned by the two KABLE experiments lent impetus to its transfer to the operational Network beginning with DSS 14 and DSS 25 at Goldstone.

The first two missions that would be carrying Ka-band downlinks to demonstrate an operational rather than an experimental capability in the DSN were the New Millennium mission DS-1 and the Cassini mission to Saturn.

DS-1 was a technology demonstration mission with secondary scientific objectives. Primary communications would be conducted on X-band, and DSS 25 was to provide a Ka-band receive capability as an operational technology demonstration. DSS 13 would also provide some analytical support. DS-1 would not be launched before the middle of 1998.

Cassini also planned to use X-band for its primary telemetry and radio metric support, but, additionally, it planned an extensive project program that would be accomplished using a combination of S-, X-, and Ka-band downlinks and X-band and Ka-band uplinks. The Ka-band uplink and downlink were required to support the Cassini Gravitational Wave Experiment in 2001.

While the DSN telecommunications engineers had been pursuing a path leading to an operational Ka-band capability in the Network, spacecraft telecommunications engineers had been pursuing a somewhat parallel path in developing an X-band/Ka-band transponder for future spacecraft. The NASA Deep Space Transponder (DST) had been in development since 1991 and was intended for first use with *Cassini*, at that time planned for launch in 1996. It would replace the existing S-band transponders, which, with an external S-band-to-X-band down-converter to provide the X-band capability, had been used on all previous planetary spacecraft. Using conventional spacecraft technology, the DST contained an automatic phase-tracking receiver for X-band uplink only and an X-band exciter to drive redundant downlink X-band transmitters. It provided appropriate reference frequency signals to devices external to the DST for the generation of independent Ka-band and S-band downlink signals.

The *Cassini* spacecraft was launched in October 1997, carrying the DST into space for the first time. *Cassini* would depend on the DST for its primary spacecraft communications links with the DSN; uplink and downlink on X-band for telemetry, command, and radio metric data; and downlink only on Ka-band and S-band for project and gravity-wave experiments.

The Ka-band transponder, also known as the Small Deep Space Transponder, had been under development since 1995 and was designed specifically for Ka-band uplink and downlink operation.[18] It included a selectable X-band capability that could be switched in or out as required, as well as several state-of-the-art components, including sampling mixers, a Ka-band dielectric resonator oscillator, and microwave monolithic integrated circuits (MMICs) to perform the functions of up and down frequency conversion, modulation, and amplification. It was proposed for first use as a telecommunications evaluation experiment on DS-1, to be launched in 1998.

Ka-band was definitely on the move in the DSN in 1997, but its arrival as an operational capability lay several years in the future.

### Orbiting VLBI Subnetwork

As discussed earlier in this chapter, Space Very Long Baseline Interferometry (SVLBI) was a cooperative project among NASA, ISAS, and ASC, representing space agencies from the United States, Japan, and Russia. ISAS provided the VSOP (HALCA) spacecraft, ASC was to provide the RadioAstron spacecraft, and the Russian tracking stations and NASA provided the SVLBI subnet of four tracking stations. One of these stations was the existing 14-meter NRAO Green Bank station in West Virginia. The other three antennas were built by NASA specially for this cooperative project and, at their completion in 1996, became part of the Deep Space Network. One antenna, with its unique electronics, was installed at each complex. Within the DSN, they were referred to collectively as the Orbiting VLBI (OVLBI) 11-meter subnet and designated DSS 23, DSS 33, and DSS 53 for Goldstone, Canberra, and Madrid, respectively. However, from the overall project viewpoint, they remained part of the SVLBI subnet.

The main functions of 11-meter stations were to automatically acquire and track the spacecraft X-band and Ku-band downlinks, generate and provide two-way integrated Doppler data to the DSN Navigation Subsystem; provide uplink to the spacecraft with a phase-stable reference frequency tied to the DSN Hydrogen Maser Frequency standard at each site; and receive, demodulate, and record the 144 Mbps downlink telemetry data in special VLBA and/or S-2 data format. The spacecraft data would be delivered to the project for later correlation with data from the co-observing ground telescopes. These functions were to be performed autonomously, without the need for operator intervention except to change recording tapes, at a frequency of 4 passes per day, 7 days per week. Interfaces with the existing DSN systems would provide the new antennas with frequency and time references; monitor and control functions; and the necessary schedule, frequency prediction, and antenna pointing and orbital state vector information to enable autonomous operation.[19]

Initial studies in 1990 had shown that considerable cost savings to NASA would result from the use of commercially available resources, rather than JPL "in-house" resources, to provide the antennas. A comprehensive set of technical design requirements was prepared in 1991, and after due process, a contract for the design and implementation of three high-precision 11-meter antennas and associated electronics and software as a "turnkey" package was awarded to Scientific-Atlanta (S-A) Corporation in September 1991.

JPL was responsible for selecting and preparing the sites and providing access roads, antenna foundation, buried cable conduits, air-conditioned buildings, power, water, and related facilities.

Although the design was based on an S-A standard, the 11-meter production antenna, a great deal of new development was necessary to meet the extremely tight design requirements for frequency and phase stability required for the intended OVLBI application.[20]

The functional block diagram in Figure 6-13 shows the interfaces between the 11-m antenna in the OVLBI subnet and various systems of the Network.

Each station in the new subnetwork contained two new subsystems: the OVLBI Tracking Subsystem (OTS) and the OVLBI Data Subsystem (DTS).

The OVLBI Tracking Subsystem included the 11-meter-diameter antenna, on an azimuth/elevation mount, with a third "tilt" axis to allow for a direct overhead pass without loss of tracking data due to the keyhole effect inherent in AZ/EL mounts. Concentric, five-horn monopulse feeds in a cassegrain subreflector configuration handled uplink and downlink signals at X-band, while the center horn also acted as a common receiving aperture for Ku-band. The Ku-band monopulse error signals were derived from a TE21 mode coupler at the base of the horn. Low-noise amplifiers, microwave components, tracking receivers, antenna-control servos and data receivers and demodulators provided for antenna pointing and downlink data reception and demodulation. Frequency converters and local oscillators driven from computers in the Data Tracking Subsystem provided the important Doppler compensation and signal coherence functions. The uplink for RadioAstron was provided by a small 5-watt solid-state X-band transmitter, while the uplink for VSOP was provided by a 0.5-watt Ku-band transmitter.

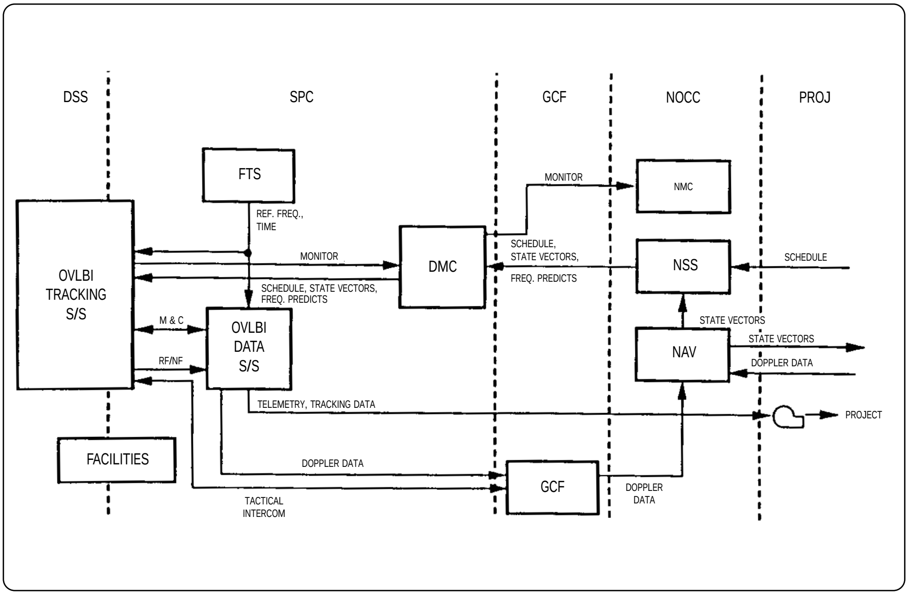


Figure 6-13. OVLBI Subnetwork functional block diagram. The following abbreviations are used in this diagram:

| | |
|---|---|
| FTS | Frequency and Timing System |
| DMC | DSN Monitor and Control |
| NOCC | Network Operations Control Center |
| NMC | NOCC Monitor and Control |
| NSS | NOCC Support Subsystem |
| NAV | NOCC Navigation |
| DSS | Deep Space Station |
| SPC | Signal Processing Center |
| GCF | Ground Communications Facility |
| PROJ | Flight Project Mission Operations Teams |
| S/S | Subsystem |

On these antennas, special measures were taken to minimize the effect of temperature variations on the phase stability of the X-band and Ku-band signals. Transmission of these signals between the antenna and the Control Room was carried on fiber-optic cables, and all frequency conversion equipment was located in the temperature-regulated Control Room. The temperature of microwave and optical equipment mounted on the antenna itself was maintained to within ±1.0 degrees of normal by an independent, proportional air-conditioning system. To further enhance phase stability, the fiber-optic cables between the antenna and the Control Room were buried six feet below ground level. Except for routine maintenance and changing of recording tapes, the station was fully operated by a ground station control computer as part of the OTS.

The OVLBI data subsystem contained various components that were peculiar to the VSOP and RadioAstron missions. A Doppler compensation computer drove the local oscillators in the Tracking Subsystem, which programmed out the expected Doppler frequency shift on both the uplink and downlink. A Doppler extractor integrated the Doppler frequency shift and provided this data to the DSN Navigation Subsystem for calculating the precise spacecraft position. After decoding, the telemetry data containing the VLBI observations from the spacecraft were recorded digitally in a special Very Long Baseline Array (VLBA) format. An additional interface to provide the VLBI data to the Canadian S-2 recording subsystem was added later.

In August 1995, four years after the award of the contract, factory acceptance testing of the first two systems for Goldstone and Canberra was successfully completed at Scientific-Atlanta. The hardware performed well, and performance against critical requirements relating to antenna gain-to-system noise temperature (G/T), phase stability, Doppler compensation, tracking accuracy, and telemetry bit error rate was well within specification. There were, however, a significant number of software anomalies which would be corrected over the following weeks. The Goldstone system was dismantled and prepared for shipping, while the Canberra system was retained on the antenna test range to provide a test-bed for clearing the software anomalies. The Canberra system was shipped a few weeks later, but the system for Madrid was delayed by shipping and other problems and did not reach the Madrid Complex until May 1996.

By then, the Goldstone system (DSS 23) was acquiring and tracking the SURFSAT spacecraft automatically without operator intervention at X-band, as well as generating two-way Doppler on a regular basis. The SURFSAT tracks were continued throughout the year to gain experience, while the Doppler data was evaluated for quality and accuracy and the last of the software problems were worked on.

A photograph of DSS 23 at the Goldstone Apollo Site with the DSS 24 BWG antenna in the background is shown in Figure 6-14.

In May and June, while the Canberra system (DSS 33) was completing its onsite system acceptance testing, assembly of the antenna for DSS 53 began at the Madrid site. By the end of 1996, all three 11-m antennas had been completed and most major prob-

Figure 6-14. DSS 23, 11-meter OVLBI antenna at Goldstone, 1996.

lems with the DPRG and the Doppler and phase generation software had been solved. Full end-to-end capability between a ground station (DSS 33) and the VLBI correlator at Socorro, New Mexico, was demonstrated for the first time in December, using X-band data from the SURFSAT spacecraft. At that time, none of the 11-m stations had yet been exposed to a Ku-band downlink, and the VSOP launch, set for February 1997, was then just over two months away.

In mid-January 1997, the SURFSAT spacecraft was commanded to switch its downlink from X-band to Ku-band to give the new 11-m stations some experience in routine tracking at the frequency they would be seeing for the VSOP downlink. For the next four weeks, all 11-m stations engaged in routine tracking of the SURFSAT Ku-band downlink, while final software deliveries were installed and preparations were made for the start of VSOP inflight operations.

The VSOP launch took place on 12 February 1997, and the first Ku-band track of HALCA, as it became known after launch, was made at DSS 23 on 20 March. With minor exceptions, 11-m subnet support for HALCA operations in 1997 was satisfactory and is described earlier in this chapter. In the longer term flight operations environment, however, the 11-m subnet required significant operations and engineering effort from JPL and the Complexes to meet most of its design specifications.

## Emergency Control Center

Each of the facilities that compose the DSN had a unique set of policies and procedures to cover emergencies and disasters that might occur in its own particular locality. The response of each facility to an emergency situation is determined by its own set of standard emergency procedures. Should the capability of the overall Network be affected by the local emergency or the steps taken to deal with it, the Network situation would be handled by the Operations Chief at the NOCC using whatever alternate resources were at his disposal at the time. However, the loss of the NOCC at JPL, for whatever reason, would critically impair the ability of the entire Network to continue support for inflight spacecraft.

Aware of this situation, the Galileo project had, in 1995, already developed a capability to conduct the critical "insertion into Jupiter orbit" phase of its mission from Goldstone in the event that a natural disaster precluded operations at JPL. A key feature of this fairly basic emergency center was the ability to send commands to the *Galileo* spacecraft from any DSN 70-m antenna, independent of support from the regular Galileo mission control center at JPL.

As a consequence of the growing perception of Network vulnerability to the occurrence of a disaster at JPL, NASA Headquarters soon requested that DSN develop and publish an official Network Disaster Plan. The Network Disaster Plan recognized the potential for disablement of the NOCC due to earthquake, bomb threat, fire, or industrial dispute, and established appropriate procedures to be followed by Network personnel. The procedures involved the relocation of basic NOCC and mission control activities to an alternate location at the Goldstone Deep Space Communications Complex (GDSCC), located about 120 air-miles northwest of JPL. There, in 1996, a permanent new facility called the Emergency Control Center (ECC) was implemented, with voice and basic data communication capabilities, specifically for the purpose of continuing Network and mission control activities on a limited scale in the event of a disaster at JPL.[21]

In its original concept, the ECC was intended to accommodate only the DSN personnel involved with Network control. It quickly became evident, however, that the spacecraft and mission control facilities that were accommodated in the same Space Flight Operations Facility (SFOF) building at JPL as the NOCC were equally vulnerable to the effects of a disaster. Under the direction of the Telecommunications and Mission Operations Directorate (TMOD), the design was broadened to include these latter capabilities in addition to those required for Network control, and the facility became the TMOD ECC.

In its basic form, the TMOD ECC consisted of a central router which could be connected, on demand, to the Goldstone Signal Processing Center (SPC) via an ethernet link and to the SPCs at Canberra and Madrid via permanently available and dedicated voice/data communication circuits. By design, the circuits to both of the overseas sites bypassed the high-earthquake-risk Los Angeles area. In the event of an emergency, the Complexes would be instructed to patch their communications circuits to alternate communications routers which would redirect their communications traffic to the ECC at Goldstone rather than to the NOCC at JPL.

Within the ECC, an ethernet LAN connected the central router to several Hewlett-Packard and Sun Microsystems high-capacity workstations arranged in a 10-base T-hub configuration. Most of these were for the use of spacecraft and mission controllers in carrying out navigation, command, telemetry data handling, and sequence generation functions. Network control functions and the generation and dissemination of prediction data products for the antenna pointing, radio metric, telemetry, and frequency control subsystem were carried out at a large VAX workstation. A DSN data base was kept current by frequent downloading of current data from the active Network support subsystem in the NOCC. Likewise, flight project software for the spacecraft and mission workstations was updated on a regular basis to reflect all changes and revisions.

Funding for implementation of the ECC task was in place by mid-1996, and responsibilities for development, planning, and implementation were assigned. The ECC was to be located at the Echo site at Goldstone in the vacant control room of the DSS 12 antenna, which had been decommissioned from DSN service earlier in 1996. Under pressure to be ready prior to the Cassini launch in October 1997, progress was rapid. By early 1997, the workstations were installed in the ECC and testing had begun. Late deliveries of the remaining equipment and a "freeze" on all new implementation activity in the Network during the *Mars Pathfinder* landing and Mars surface operations in July delayed the completion of the work until mid-August, when Cassini and Ulysses mission controllers were able to begin evaluation of the ECC for flight operations support. The first tests with Canberra and Madrid used 28-kilobits-per-second communication circuits routed through JPL, since the special 512-kilobits-per-second direct circuits between the ECC and the overseas sites had not yet been made available to JPL.

Meanwhile, the Cassini project had developed a new launch "constraint" requirement for an independent back-up for the existing Cassini Launch Operations Center at JPL. Fortunately, the 28-kilobits-per-second circuits could be used to satisfy the newly imposed the Cassini launch criteria in the event of further delay in the availability of the wide-band 512-kilobits-per-second circuits. A few weeks later, these circuits did become available, just in time to fully test the system with the overseas sites and to satisfy the new Cassini requirements.

The TMOD Emergency Control Center was reported to be operational for all JPL flight projects on 6 October 1997. *Cassini* was successfully launched nine days later, with the ECC providing back-up for its prime Launch Operations Center at JPL.

The ECC was first used for full in-flight mission support by *Galileo* at the end of October 1997. A complete track, including planning tasks and spacecraft command functions, was run successfully from the ECC by Galileo flight operations personnel. Similar demonstrations were planned to familiarize Ulysses, Voyager, and Mars Global Surveyor operations personnel with the capabilities (and limitations) of the new facility. In due course, these demonstrations came into regular scheduled use as a means of keeping the ECC in a state of readiness and exercising its potential users in emergency awareness.

## OTHER ASPECTS

The years 1996–1997 brought to a close the traditional form of mission operations that the DSN had employed to support all of NASA's planetary missions, and many of its lunar and Earth-orbiting missions, for almost forty years. New, more efficient, and less costly ways of conducting mission operations, including a move to Ka-band frequencies, were being introduced in the Network to match NASA's call for "faster, better, cheaper" missions. In the opening years of the Cassini Era, Mars Global Surveyor and Mars Pathfinder, the first planetary missions designed to new guidelines, were launched on a fast track to Mars. *Cassini*, the last planetary spacecraft based on the old principles, began its long mission to Saturn.

While the proper business of the DSN was always the support of NASA's inflight spacecraft missions, "mission operations" represented only one aspect of DSN history over the period covered by this book. Technology, science, and organization, although not directly involved with "mission operations", were also essential to the growth, scientific stature, and fiscal well-being of the Network during that time.

To this point, the narrative has emphasized "mission operations" in terms of five major eras of planetary missions from 1957 though 1997. With that completed through the Cassini Era, we turn now to consider other aspects of DSN history, beginning with the growth of technology in the DSN.

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